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EVALUATION OF FIREWORK MORTARS

E. Contestabile, R.A. Augsten, R.R. Vandebeek
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EVALUATION OF FIREWORK MORTARS

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ABSTRACT

The objective of this study was to evaluate the performance of firework mortars by causing shells to explode in them. Tests were performed at nominal temperatures of 20°C and -20°C for both star and report shells. Events were recorded via video, still and high speed photography. The results do not indicate serious faults with any particular mortar material.

The study reports the results of approximately 280 mortar bursts and attempts to relate the data to several concerns. The requirement for a maintenance-free mortar, one that can withstand repeated use and, in case of a failure, a "fail-safe" mortar. Thus, when it comes to use, an operator must always make a judgement as to whether a paper mortar can take another firing. Steel mortars have always been relied upon to take many firings yet everyone realizes the degree of danger if one was to burst.

The results indicate that all mortars, except the Schedule-40 steel which burst only at very low temperatures, ruptured and produced fragments under most conditions. However, when one considers the consequences of an accidental burst, the mass and distance to which fragments were thrown can be used as safety criteria. The fragments from the fibre reinforced epoxy mortars had a range of approximately 30 m, the paper 70 m, the plastics 70 m and the metal mortars 120 m. The lethality of these fragments are not considered here but will be the topic of a future report.

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Keywords: Fireworks mortars, fireworks mortar bursts, mortar fragments.

ÉVALUATION DE MORTIERS POUR PIÈCES PYROTECHNIQUES

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RÉSUMÉ

Cette étude avait pour but d'évaluer la résistance de mortiers à l'intérieur desquels on a fait exploser des bombes. Ces essais ont eu lieu à des températures variant de 20°C à -20°C, tant pour les obus à étoile que pour ceux à fort détonation. L'éclatement des mortiers a été enregistré sur band vidéo, sur photographies prises à grande vitesse et sur photos empruntées à un film. Selon les résultats, aucun mortier ne semble présenter de défectuosité grave.

L'étude rapporte les résultats d'environ 280 tirs de mortiers, résultats qu'elle tente d'évaluer selon divers critères. Le mortier idéal, par exemple, ne nécessite pas d'entretien, peut être utilisé trés souvent et offre une "sûreté intégrée" en cas de défaillance. Ainsi, chaque fois qu'il utilise un mortier en papier, l'artificier doit juger si ce mortier d'acier pour affectuer le plus grand nombre de tirs, on sait bien quel danger celui-ci représente s'il vient à éclater.

Au cours de ces essais, les mortiers ont tous éclaté en fragments sous le choc des explosions auxquelles on les a soumis. La seule exception est le mortier d'acier, de type Schedule-40, qui n'éclate qu'à de trés basses températures. Cependant, si l'on tient compte des conséquences d'un éclatement accidentel, on peut retenir, comme critère de sécurité,la masse des fragments et la distance à laquelle ils sont projetés. La portée des fragments variait selon la composition du mortier: époxy renforcé de fibres: 30 m; papier: 70 m; plastique: 70 m; métal: 120 m. Le danger que ces fragments représentent pour la vie fera l'objet d'un rapport à venir.

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Mots clés: Mortiers pour pièces pyrotechniques; tirs de mortier; fragments de mortier.

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INTRODUCTION

The aim of this study was to evaluate the performance of the mortars that are currently on the market and make recommendations as to the best performers and modifications that may best improve their safety in use. This was accomplished by causing various sizes of shells to explode in mortars of corresponding sizes and made of the different materials normally in use. Tests were performed at nominal temperatures of -20°C and 20°C.

During the past few years, the fireworks industry has become particularly sensitive to the safety of their operations. The reasons for this may be;

1. society's increasing awareness of safety and, in its drive to reduce injuries has led to more stringent labour codes,
2. skyrocketing insurance rates, and
3. fundamental economics.

Firework mortars have always been a concern and major efforts are currently directed in this area.

In the past, operators manufactured mortars from whatever materials were available in the marketplace. At present, the authors are aware of only two mortar types that are manufactured from basic materials for this very specific function in North America. They are, the sheet steel with integral bottom and the moulded HDPE. Another mortar is being manufactured from specially made HDPE pipe and a hardwood plug that are rigidly fastened together with through-bolts. Two other types that could also be considered in this category are steel pipe with welded bottom and High Density Polyethylene (HDPE) pipe with welded HDPE caps. This latter design is being considered and evaluated by several firms.

As part of a major thrust by the Canadian Explosives Research Laboratory (CERL) to investigate concerns in this field,

(1, 2, 3, 4, 5) support was obtained from various firms (See Appendix A) including the American Pyrotechnics Association (APA).

The APA began testing mortars in racks about two years ago and have produced a valuable video on this topic. CERL decided to take the more fundamental approach of evaluating individual mortars.

The program was defined to include approximately three tests on each of 76, 102, 127, and 155 mm mortars made from the most common materials, at two nominal temperatures, and tested with two types of shells. The two 'standard' shells included a star shell renowned for being quite energetic and available in 76, 102, 127, and 155 mm and a report shell available in 76 and 127 mm sizes. A parallel and related study, cited as reference (2), determined the TNT equivalent of the above report shells. When one includes preliminary trials, approximately 280 tests were performed.

The question will undoubtedly arise as to the statistical meaning of the results given so few tests per specific set-up. A study with the outlined scope will have some shortcomings, however, attempts were made to temper this with careful data collection.

Although, most mortars perform well under normal circumstances, the results of this project indicate that some may be better than others in certain situations when one considers the lethality of the fragments from an accidental burst. Thus, the study can be used as a guide and as a starting point for the many questions that it has given rise to and that must be answered.

WHAT CONSTITUTES A GOOD MORTAR?

At the very conception of this program, the question arose as to what characteristics constitute a poor or alternately, an

ideal mortar. What traits would disqualify a mortar from being considered as adequate?

An ideal mortar would be a tube (with bottom) capable of withstanding very high pressures but would have no mass (just in case it ever burst). One can only guess at the performance of such a mortar. For practical and safety reasons, a mortar should also be as maintenance-free as possible.

Since two phases must be considered when evaluating the effectiveness of mortars, first, the ability to withstand the high pressures and secondly, the lethality of the fragments if the mortar fails, then, the choice should be based on a balance between (1) materials of high strength and (2) "fail-safe" type materials (materials that would absorb sufficient blast energy to reduce the lethality of the fragments). Although, a relatively light mortar could be manufactured, the unrealistic opposite could also be considered. That is, a very massive mortar designed to withstand pressures higher than those developed by exploding fireworks shells. Since such a mortar is not practical, manufacturers initially attempted to achieve the high strength by turning to steel. Confidence, development of new materials and economics led to substitute materials. However, due to high development costs, research into a high strength, low mass mortar has not occurred.

And now, questions regarding the 'plug'. What is the role of this rather massive component? In this study, one plug was thrown 85 m! What kind of wood and grain orientation is best? Do mortars with integral plugs perform any better? Whenever such questions arise, the most common comment and reminder is that mortars are normally buried. This is true, but there are reports of plugs being thrown when mortars in racks or buried in snow or in sand boxes have accidentally burst.

The fastening system must also be considered when evaluating mortars with plugs. Arguments can be given for light or rigidly

fastened plugs. The fasteners themselves can be questioned. Although screws and bolts make better fasteners, they are normally more massive than nails or staples. Again, the best plug/fastener system should minimize the number of lethal fragments in an accidental burst. And again, proper burial of mortars could render most mortar burst accidents safer.

Comments made throughout this report derive from the view that a rigidly fastened plug is the safest. Although this is not necessarily the case, this must be taken as a reference for two main reasons. First, manufacturers tend to strive for the best fastener system in the belief that it will increase the strength and the life expectancy of the mortar. Secondly, it is practically impossible to manufacture a mortar with a built-in weakness that would guarantee a "fail-safe" mode in the case of an accidental burst.

TEST MORTARS AND SHELLS

Many mortars were submitted for evaluation under this program. Initial observations indicated that the majority were well constructed but some did have flaws. Some details of the mortars and the test shells are given in Appendices B and C, respectively. What follows is a description of and comments on the shells and each type of mortar received. A section on mortar plugs is also included since they are a vital component of a mortar.

Test Shells

The relevant information for the star shells used is listed in Appendix C. Two types of star shells and one of report shells were used. The shells were prepared as outlined in the Experimental set-up section.

Mortar Plugs

Basically two types of plugs were observed to be used. Some were manufactured from either one piece or laminated pieces of wood with the grain parallel to the mortar. These plugs were normally well made because they were turned to the proper diameter on a lathe or similar equipment.

The other type of plug was assembled by nailing nominal 5 cm thick planks together to obtain the required thickness. The grain of each piece would be oriented perpendicular to the grain of the adjacent piece. Most of these plugs were in poor shape. Many were out-of-round, cracked or had pieces missing. This resulted in gaps between the plug and mortar.

The plugs were installed with either steel staples, nails (spiral or roofing) or a combination of both or with screws. In none of these methods were attempts made to strengthen the assembly by increasing the fasteners' bearing surface (i.e. use of washers) or were the number of fasteners or their position consistent within each type of mortar.

Other observations on all plugs included poor installation, one batch with only one nail and another with no nails at all. Many of the nails were either not or poorly seated against the mortar wall.

Paper - Plain - Convolute Wound Mortars (Paper-P-S)

The plain, non-impregnated, convolute wound mortars were found to be in poor condition. Although new, the paper layers could already be seen separating at the mortar ends. The 76 mm size had the plug with the grain oriented parallel to the tube while the 102 and 127 mm sizes had plugs with the grain perpendicular to the tube. All the plugs were fastened with four nails. These mortars of

Spanish origin had metric sizes printed on the mortar wall. They were supplied in 76, 102 and 127 mm sizes.

Paper - Impregnated - Spiral Wound Mortars (Paper-I-S)

The impregnated, spiral wound mortars were in very good shape. The ends did not show any sign of the paper layers separating or unravelling. The plugs of the 76 mm size had the grain oriented parallel to the mortar and were fastened with staples while those of the 102 mm had the grain perpendicular to the tube and were fastened with staples and roofing nails. Few mortars were supplied and then only in 76 and 102 mm sizes.

Paper - Impregnated - Convolute Wound Mortars (Paper-I-C)

The impregnated, convolute wound mortars were well made. Although the supplier stated that these were impregnated paper mortars, it is suspected that they were not. The plugs were nailed and had the grain parallel to the mortar. An epoxy seal/adhesive was also used on the inside surface of the plug and between the plug and mortar resulting in no gaps and a good finish. Very few of these mortars were supplied and in only two sizes, 102 and 127 mm.

High Density Polyethylene (HDPE) Mortars With Plug

The plugged HDPE mortars were not very well made. The ends were neither cut squarely or cleanly and as a result some could not be stood on end. An observation made on HDPE mortars is that there always seems to be some shrinkage where it is cut. As a result, the diameter of the mouth of a mortar is always reduced. Two firms submitted HDPE mortars with wooden plugs.

Sample 1

Sample 1, was available in 76, 102, 127, and 155 mm sizes. Most of these mortars had plugs made with the grain oriented perpendicular and fastened to the tube with staples.

Sample 2

Sample 2 was available in only two sizes 127 and 155 mm. The single piece plugs were fastened with nails and had the grain oriented parallel to the mortar, however, the wood seemed to be in poor shape. Some plugs were cracked and had shrunk away from the mortar wall resulting in gaps.

High Density Polyethylene (HDPE), Moulded Mortars

This is one of the newest mortar designs on the market. The blow mould fabrication process results in a very consistent product with the wall thickness increasing toward the bottom. No comment can be made on plug/tube assembly due to the one piece design. These mortars were supplied in 76 and 102 mm sizes only.

Acrylonitrile-Butadiene-Styrene (ABS) Mortars (ABS1)

These mortars will be referred to as ABS1 to simplify discussion in this report. The ABS1 mortars had the ends cleaner cut than the HDPE. All plugs had the grain oriented parallel to the mortar. Most of the plugs were nailed except for a few of the larger diameter ones that were screwed to the mortar. These mortars were supplied in 76, 102 mm sizes.

Acrylonitrile-Butadiene-Styrene (ABS)+Hardwood Plug Mortars (ABS2)

These mortars (denoted as ABS2) were manufactured at CERL to determine if there was any noticeable effect when plugs were manufactured from laminated hardwood, were close-fitting and the grain oriented parallel to the mortar. The plugs were made longer than normal to provide sufficient surface for the fasteners. This resulted in a mortar having a rigidly fastened plug. They were installed with two rows of screws countersunk into the plastic. These mortars were manufactured in three sizes, 76, 102 and 155 mm.

Fibre Reinforced Epoxy (FRE) Mortars

The tube used to manufacture the fibre reinforced epoxy mortars is commercially available as electrical conduit for above and below ground use. These mortars were generally well constructed except that the number of fasteners varied from 0 (loose plug) to 1, 2, 3, 4, and 8 per mortar. The plugs of all sizes except the 155 mm had the grain oriented parallel to the mortar. Because the manufacturer was experimenting with the 155 mm size, nominal 5 cm thick, stacked lumber was used to make plugs for these mortars. Many of the plugs were manufactured from wood that was in poor condition. Any defect with the plugs was amplified by the nearly perfect roundness of the FRE pipe. These mortars were supplied in 76, 102, 127, and 155 mm sizes.

Aluminum Conduit Mortars

The aluminum conduit mortars were assembled with plugs which had the grain oriented parallel to the tube. Again, due to the near perfect roundness of the conduit, any defects in the plugs tended to leave gaps. The plugs were fastened with T-shaped nails to the conduit. These mortars were supplied in 76, 102, 127, and 155 mm sizes.

Sheet Steel Mortars

Again, as a result of the manufacturing process, the sheet steel mortars with integral convex bottom were very well made and of consistent quality. Bottom, seam and collar band were all spot welded. The painted mortars were received in individual cardboard boxes. They were the only mortars identified by size and colour-coded labels that also included instructions on use. These mortars were supplied in 76, 102, 127, and 155 mm sizes.

Schedule-40 Steel Mortars

The schedule-40 steel mortars were specifically made for these tests. In the initial trials, the bottoms were butt-welded to the ends of the pipe. Due to the results obtained in the preliminary tests, the design was later modified. The bottoms were welded a short distance from the end and inside the pipe. These mortars were manufactured in 76, 102, 127, and 155 mm sizes.

EXPERIMENTAL SET-UP

Basically, a mortar was hung in the centre of a series of 60 cm wide by 240 cm high frames, arranged to form a 3.5 m diameter circle. The frames, placed on a gravelled pad, held witness panels that would catch the fragments if the mortar burst. Seldom were all the frames fitted with witness panels since extensive damage was often caused by the blast pressures. As a result, a minimum of three panels were frequently used. One panel was inserted in the frame behind the mortar and facing the cameras. The two others were located on either side of the mortar and with their sides approximately parallel to the line of sight of the cameras to facilitate monitoring their radial displacement. Markers were placed on the ground at 5 m intervals from the mortar location to facilitate recording the fragment distance.

It was decided very early in the test program to place the mortar in a position that would reduce variables so as to provide reasonable reproducibility and would simplify recording all the parameters of interest. The set-up should also allow the free, unobstructed projection of the fragments. Thus, the set-up was designed to reduce variables that would complicate the assessment of the results, give maximum observation capability, allow the systematic collection of the fragments, and ensure maximum reproducibility.

All the data was recorded photographically and with video. A side-on pressure gauge was used to monitor the blast overpressures and some 30% of the tests were recorded with a high speed camera running at 500 frames per second.

The photographs in the album have been arranged in the same order as the tests appear in Table 1. There are several reasons why it may seem that the tests were not performed in a systematic fashion. Initial tests were performed to determine the typical effect that could be expected from the different materials, shells, temperature, etc. An attempt was made to perform the low temperature tests at low ambient temperatures and if this was not possible, only the mortars made of low thermal conductivity materials were tested at such times. Following this, the erratic test order was based on the availability and the delivery of the mortars and shells from the various contributors.

When the mortars were first received, they were labelled and weighed. Two holes were then drilled close to the opening to facilitate hanging them in the frame. When tested, only the mortars were temperature conditioned. The shells were at or close to the ambient temperature. The mortars were placed in an insulated container and liquid carbon dioxide was used as the cooling medium.

It will be noticed that tests were performed at several temperatures about the two nominal temperatures of -20°C and 20°C.

Normally, the mortars were cooled to 5°C lower than those temperatures indicated in the video, photographs and debris distribution graphs. This was to compensate for the heat gain during the time taken to hang, charge the mortar and function the shell. The nominal 20°C tests were normally performed at the ambient temperature. All the reported temperatures were rounded to the nearest 5°C.

Table 1 - Mortar evaluation tests

Mortar Type	Star Shells								Report Shells			
	Temperature -20°C				Temperature 20°C				Temp -20°C		Temp 20°C	
	Sizes/mm				Sizes/mm				Sizes/mm		Sizes/mm	
	76	102	127	155	76	102	127	155	76	127	76	127
Paper												
-Plain, Conv	FXX	XF	XF	N/A	XX	F	FFX	N/A	XXF	XFFF	XFF	FXF
-Impreg, Spir	N/A	XFF	N/A	N/A	XX	XF	N/A	N/A	XXF	N/A	FFX	N/A
-Impreg, Conv	N/A	FX	XFX	N/A	N/A	FXX	N/A	N/A	N/A	XF	N/A	N/A
HDPE												
-Plug-Sample 1	XXX	XX	XX	XX	FX	XF	XFX	FFX	XX	XXF	XFX	XFX
-Sample 2	N/A	N/A	F	XF	N/A	N/A	XF	XXF	N/A	FX	N/A	XXF
-Moulded	XXX	XX	N/A	N/A	FX	FFF	N/A	N/A	XXF	N/A	XXF	N/A
ABS												
-Regular	FX	F	N/A	N/A	XX	XFF	N/A	N/A	FXX	N/A	XXF	N/A
-Hardwood Plug	XX	F	N/A	F	N/A	FX	N/A	F	F	N/A	FXX	N/A
Fibre	XX	XXF	XFF	X	XX	XFF	XXF	X	XXX	XX	XXX	XXXX
Aluminum	X	X	X	X	X	XF	XF	XF	X	N/A	XXF	XXF
Steel												
-Sheet steel	XXF	XFF	XFF	XXF	FX	XXF	XFF	XFF	XFF	FFX	FFX	FFX
-Sched-40 pipe	XX	X	X	XXFF	F	XF	XF	XF	XF	XXXFF	XFX	XFX

X - Test performed
F - Test performed and filmed (High speed)

Several tests were performed at extremely low temperatures to determine the limits of some of the mortars, especially steel. Tests to determine the effect of higher temperatures were also performed in the summer on some of the plastic mortars by leaving them to warm in the sun. Many of the initial tests which led to the final set-up design have not all been reported.

A shell was prepared by removing and placing the lift charge in a small plastic bag. An electric match was taped to the delay element, the shell was lowered in the mortar and the lift charge dropped on top of the shell. The mortar was now ready to hang in the frame.

The mortars were hung so that the centre of the shell in the mortar was 1 m above the ground. This height corresponded to the height of the blast pressure gauge which was located at a distance of 2 m. A steel wire was initially used to hang the mortar. In certain tests, the force from the lift charge caused the wire to break and the shell to burst in the mortar when on the ground. Sometimes, the explosion of a star shell would damage the suspension system and rocket the mortar toward the ground. A 155 mm steel mortar was driven approximately 30 cm into the ground. Consequently, progressively heavier wire was used, eventually switching to a chain bolted to the mortar.

DATA TREATMENT

As already stated, the data from the actual test was recorded with video, still and high speed photography and a blast pressure gauge.

Once the shell was functioned, the area was thoroughly searched for mortar and plug fragments. Except for the very small ones, the pieces were marked with the distance value from the origin. Although an attempt was made to recover at least 90% of the initial mass, it was sometimes impossible. The area surrounding the gravel pad upon which sat the frames, was grass covered, and even maintained as short as possible, many of the fragments were often camouflaged. The percent recovered mass is indicated in the Debris Distribution graphs assembled in the photo albums. The recovered mass at times is shown to be higher than the initial mass. This

occurred either from shell material remaining attached to the mortar or from gravel being embedded in the mortar or plug pieces when they were driven onto the pad.

The mortar pieces were photographed and weighed. Debris distribution plots were then generated with the number of mortar and plug pieces and mortar and plug mass as a function of distance. These graphs were then photographed. Thus for every mortar there are two photographs. Both photographs show the test number, the mortar size, the type of mortar, the test temperature, and the shell type. In addition, the debris distribution photographs show the mortar number, the initial and final mortar mass and the percentage of the mass recovered.

When many small pieces (mass less than 1 g) were found, as with the fibre reinforced mortars, they were weighed together rather than individually. A debris distribution graph where this occurred will show very many pieces but little mass.

RESULTS

The results from this project have been collected and presented as a series of approximately 550 photographs. Accompanying this report and photograph album is a video composed of real time tests and still and high speed photographic records. A list of the tests that were performed under the various parameters, appears in Appendix E. Table 1 has also been reproduced as Table 2, shown below, to provide an indication of the extent of damage sustained by the mortars.

Table 2 - Mortar evaluation results

Mortar Type	Star Shells								Report Shells			
	Temperature -20°C				Temperature 20°C				Temp -20°C		Temp 20°C	
	Sizes/mm				Sizes/mm				Sizes/mm		Sizes/mm	
	76	102	127	155	76	102	127	155	76	127	76	127
Paper												
-Plain, Conv	ppb	pp	bb	N/A	pp	b	bbb	N/A	BBb	BBBB	bbb	BBB
-Impreg, Spir	N/A	PPb	N/A	N/A	pP	pP	N/A	N/A	BBB	N/A	BbB	N/A
-Impreg, Conv	N/A	pp	bbb	N/A	N/A	ppp	N/A	N/A	N/A	Bb	N/A	N/A
HDPE												
-Plug-Sample 1	PPP	Pp	PP	bB	Pp	PB	PBB	BBB	Bb	BBB	BBB	BBB
-Sample 2	N/A	N/A	P	BB	N/A	N/A	BB	bBB	N/A	bB	N/A	BbB
-Moulded	SSS	bb	N/A	N/A	SS	bbS	N/A	N/A	bbb	N/A	bbb	N/A
ABS												
-Regular	bb	b	N/A	N/A	pp	PPP	N/A	N/A	bBB	N/A	BbB	N/A
-Hardwood Plug	SS	S	N/A	b	N/A	Sb	N/A	b	b	N/A	bbb	N/A
Fibre	pp	ppp	PPP	P	pP	Ppp	PPP	P	BBB	BB	BBB	bBBB
Aluminum	p	p	b	B	S	pB	PB	BB	b	N/A	bbb	BBB
Steel												
-Sheet steel	SSS	Spp	bbb	bbb	SS	SSS	bbb	bbb	bbb	bbb	bbb	bbb
-Sched-40 pipe	SS	S	S	SSSS	S	SS	SS	SS	SS	bSbSb	SSS	SSb

$ - Mortar survived
p - Plug blown out intact but tube survived
P - Plug blown out and fragmented but tube survived
b - Mortar burst but plug remained intact
B - Mortar burst and plug fragmented

SAFETY CRITERIA

Although, a full scale examination of the lethality of each mortar/plug fragment is beyond the scope of this report, it is necessary to establish tentative criteria by which the level of hazard from a bursting mortar can be quantified. The assumptions, for this preliminary examination will be that;

a) a mortar bursting in many pieces is more dangerous than one that bursts in few pieces,
b) pieces that are thrown long distances are more dangerous than those thrown short distances
c) plug pieces are more dangerous than mortar pieces

The probability to injure must be considered within the area (more correctly, volume), where an incident may occur. In a typical fireworks display, fewer people are within the "operator zone" than in the "spectator zone". Then, again, the probability of finding a higher concentration of and higher energy fragments is greater at close range, in the "operator zone", than in the "spectator zone". Thus, the three assumptions do not unduly bias either the operator or spectator.

In general, it is assumed that the probability of an injury occurring would be higher, the higher the number of fragments and the greater the distance that they travel. This may seem to bias the presence of spectators but in fact, the probability of striking and injuring an operator is very high due to the higher concentration and speed of the fragments close to the source. It can be argued that those fragments that are thrown long distances are projected at large elevation angles and may not pose a danger to the operator. A different scenario will present itself when the mortars are buried, placed in racks and/or the shells are fired electrically. Without considering the mass of the fragments and their energy, the degree of injury cannot be assessed.

The last assumption which states that the plug pieces are being assumed to be more dangerous than the mortar pieces has been made mostly to balance the effect from the low density mortars (paper) and from the fact that the plugs often carry the fasteners with them. This assumption would be more realistic for rack mounted mortars.

To cause a mortar to burst into many pieces and/or throw the pieces long distances would indicate that the burst was caused by a high energy source. This can be seen to occur as the size of shell increases or as one compares the effect of star shells with report shells. The same is true for the plug. The more energetic the source, the more plug pieces will be produced.

OBSERVATIONS

General

From the large amount of data collected one can make many comparisons. A multitude of conclusions can be derived by comparing the volume of photographs and/or viewing the video records. As examples, one can easily notice differences in the damage caused by star shells versus that of report shells or the effect of temperature on the type of fracture or fragment sizes.

It will also be noted that the 102 mm star shell is the critical size at which mortars begin to sustain substantial damage. In most materials, the 127 mm and 155 mm shells cause the mortars to burst. This undoubtedly relates to the amount of composition in the shells.

Preliminary Tests

Two sets of preliminary tests were performed. The first was to establish how the mortar should be set-up to obtain reproducible results and the effect of fragments on pressed paper board witness screens located 2 m from the mortar. Tests were performed with star and report shells at ambient temperatures with the mortar located upright on a concrete pad. On initiating the lift charge the following main observations were made.

(1) The mortar fell on its side. Then, when the shell burst, the mortar was rocketed away from the origin, often sustaining no damage. In tests with report shells where some mortars burst, many of the fragments punctured the witness screens.

(2) The shell bounced out of the mortar and functioned on the ground. The explosion threw the mortar away from the origin.

The observations indicated that this would not be a suitable set-up. As a result, the frame described earlier, was designed. The second set of tests was performed with the mortars hanging within the frame. These tests were performed at ambient temperature to evaluate certain mortar materials and to demonstrate the test procedure to various concerned parties. The results are shown in the Preliminary Test section of the photograph album and the following observations were made.

(a) HDPE+Plug - The star shell blew the plug out in two pieces but the 102 mm tube survived. In the test with the report shell, the plug was blown out whole and the bottom of the 76 mm mortar burst. In both tests, the pieces were found within a 5 m radius.

(b) HDPE Moulded - A star shell simply split the bottom section of the 102 mm mortar. The 76 mm mortar tested with a report shell burst into 17 fragments that were found to a maximum distance of 35 m.

(c) Fibre - The star shell blew the plug out intact and the 102 mm tube suffered no damage. In the test with the report shell, the plug was shattered into approximately 35 pieces and the 76 mm mortar burst producing in excess of 40 fragments. These were all recovered within a radius of 25 m.

(d) Sheet Steel - Two mortars were tested with star shells. The 102 mm mortar survived the explosion of the shell. The damage seen on the bottom of the mortar was caused when the support wire broke and the mortar struck the ground. The 155 mm mortar burst into 14 pieces including the formed plug. The fragments were found to a maximum distance of 65 m. Two tests were also performed with report shells. The 76 mm mortar burst into 19 pieces that were thrown a maximum distance of 75 m. The 127 mm mortar also burst producing larger fragments than those of the 76 mm mortar. The ten pieces were found within a radius of 55 m.

(e) Steel Schedule-40 - Two tests were performed with star shells on the same 127 mm mortar. No damage was sustained in the first test. In the second, the weld broke and the bottom was blown out. Three other tests were performed with report shells on 76 mm mortars. In one the bottom was blown off. The second survived intact and in the third, part of the weld broke. These results led to the alternate design of these mortars.

What follows are the results for the various types of mortars as obtained from the established set-up. Within each section, the effect of the temperature and shell size and type are discussed.

Paper - Plain - Convolute Wound Mortars (Paper-P-S)

The plain, convolute wound mortars were found to exhibit poor adhesion between the layers. As a result, when a mortar burst, many of the fragments would result from the paper layers separating.

Normally, a star shell caused the plug to be simply blown out, with the larger shells also causing the mortar to burst. The maximum number of fragments produced was approximately 48 and the larger pieces were thrown to a distance of 55 m.

Report shells caused all the mortars to burst in many pieces. The 76 mm shell fragmented almost every plug, whereas, the 127 mm shell normally blew the plug out whole or split it in two. Plug pieces were all found within a 15 m radius. The maximum number of fragments was 120 and they were found as far as 75 m.

An interesting occurrence is that of Test #10, where, the ignition of the report shell caused the mortar hanging system to break and the shell to burst in the mortar as it lay on the ground. The mortar burst producing approximately 30 fragments which were

thrown to a distance of 30 m. The plug remained intact and was thrown to a distance of 85 m.

Paper - Impregnated - Spiral Wound Mortars (Paper-I-S)

As already indicated, the impregnated, spiral wound mortars were very well made. When these mortars burst, the paper layers did not tend to separate as much as the mortars that were made with paper that was not impregnated.

Out of the seven tests with star shells, only one mortar burst. In the remainder, the plug was either simply blown out in one piece or split in very few pieces. The one 102 mm mortar that did burst, produced approximately 45 fragments that were thrown to a distance of 45 m.

Tests with report shells were only performed on 76 mm mortars. All the mortars burst and the plugs, with the exception of one, were fragmented. The maximum number of pieces produced was approximately 60 and were thrown to a maximum distance of 35 m.

Paper - Impregnated - Convolute Wound Mortars (Paper-I-C)

Unfortunately, only ten of these mortars were supplied. As already mentioned, it is suspected that the paper used to make these mortars was not impregnated. Witness how cleanly the layers can be seen to have separated in any of the tests where the mortar burst.

In all the trials with the star shells, the plug was blown out in one piece and only the 127 mm mortars burst. The 102 mm tubes remained intact. The maximum number of fragments produced was approximately 45 and were thrown to a distance of 45 m.

In both trials with report shells, the 127 mm mortars burst and in one, the plug fractured into 15 pieces. Approximately 20 fragments were produced in each trial and were found to a distance of 25 m.

High Density Polyethylene (HDPE) Mortars With Plugs

Sample 1

With most of the plugs manufactured with the grain perpendicular to the mortar, very few of them survived. The plugs were blown out in all the tests, with some fracturing to as many as 20 fragments with a report shell.

From the 19 trials with star shells, none of the 76 mm mortars burst, one 102 mm split and four 127 mm split at several places. In the case of the 155 mm, the mortars either sustained long splits or severe mangling in the typical stretched fashion. The maximum number of fragments in these tests was 20 and resulted mostly from the plug splitting. The fragments were found to a distance of 45 m.

The report shells caused all the mortars to burst and the plugs to split. The number of fragments ranged from approximately 15 to 30 and were found to distances of approximately 45 m. An interesting trial was that performed at -35°C. The brittle fragments produced numbered approximately 160 and were found to a maximum distance of 55 m.

Several tests in this series displayed the typical fold-back that has often been encountered by others who have tested HDPE pipe. The pipe experiences forces that cause the burst end to turn inside out.

Sample 2

These mortars were only available in 127 and 155 mm sizes and were assembled with single piece, soft wood plugs with the grain oriented parallel to the mortar. Out of the eight tests with star shells, one plug was shattered into 27 fragments, and one survived. In the remainder of the tests, the plugs split into two to six pieces. The report shells seem to have done less damage to the plugs. Out of the five tests, two plugs survived and the other three were split producing three to six pieces. All the plugs and plug pieces were recovered within a 5 m radius.

In the low temperature tests, the following results were obtained with star shells. One tube survived, one suffered splitting near the bottom end, and the other split into three pieces that were recovered at a maximum distance of 35 m. At the higher temperature three of the mortars were split as in the low temperature tests whereas, the other two suffered extensive stretching and mangling.

The damage from the report shells was more extensive. In one case, where it is suspected that the shell bounced some distance from the bottom before it exploded, the mortar burst in two pieces. In the remaining four tests all the mortars burst, producing from 8 to 24 fragments that were thrown to a maximum distance of 45 m. Two of these tests displayed the typical fold-back mentioned above.

High Density Polyethylene (HDPE), Moulded Mortars

The moulded HDPE mortars are approximately 50% lighter then their plugged counterpart. Only 76 and 102 mm sizes were available at the time of testing. Although there are plans, the blow-mould process does not readily lend itself to manufacture such mortars in larger sizes.

The star shells caused all the 102 mm mortars to split open over a short distance in the bottom area. Smaller splits or bulges were produced in the 76 mm mortars. None of the damage was accompanied by any fragments. One mortar that was warmed in the sun to 40°C showed no signs of damage. As a result, the Debris Distribution graphs do not show any fragments beyond the test point.

The report shells caused all the mortars to burst. All of the pieces indicated that stretching occurred before breaking. The number of fragments varied from about 10 to 25 and were thrown to a maximum distance of 45 m. The one mortar tested at 40°C did not show any discrepancy in the number of fragments produced except that they seemed to be stretched longer.

Acrylonitrile-Butadiene-Styrene (ABS) Mortars (ABS1)

Since most ABS mortars are being replaced with HDPE, only two sizes were available from fireworks operators for evaluation. Out of the 14 tests, 50% of the plugs survived intact, five split to a maximum of five pieces, and the remaining two split into 13 pieces.

At the low temperatures, star shells caused both the 76 and the 102 mm mortars to burst. All the plugs survived. The mortars fractured producing from 16 to 54 pieces that were thrown to a maximum distance of 45 m. As described by other researchers, there was no evidence of stretching on the fragments formed. The pieces had brittle fracture characteristics, being cleanly broken and sharp edged. In the 20°C tests with the star shells, the plugs were either blown out whole or split to a maximum of five pieces, with the mortar tube surviving all the tests. The pieces were thrown a maximum distance of 15 m.

The report shells caused all the mortars to burst and although, a couple of plugs survived intact, these shells were also responsible for causing the plugs to split into the maximum number of pieces. The cold temperature tests produced the most mortar fragments (maximum 90) that were thrown to distances of approximately 70 m.

Acrylonitrile-Butadiene-Styrene (ABS)+Hardwood Plug Mortars (ABS2)

As already explained, the ABS2 mortars were manufactured at CERL to evaluate, "proper" plug fit and assembly. The plug was blown out intact in seven out of the eleven tests. In the remaining four tests, the mortar survived intact.

In the low temperature tests with the star shells, only the 155 mm mortar burst producing 14 large fragments that were thrown a distance of 75 m. The 76 and 102 mm mortars survived intact. From the three tests performed with star shells at 20°C, including those on mortars that were sun-warmed, two mortars burst producing a maximum of 12 large fragments. They were found to a maximum distance of 55 m.

From the limited number of tests with report shells, there seems to be very little difference between those performed at the high and low temperatures. The mortars all burst, producing from 18 to 28 pieces that were thrown to a distance of 75 m. The sun-warmed mortar burst into 14 pieces.

Fibre Reinforced Epoxy (FRE) Mortars

Most of the plugs of the FRE mortars survived the tests with the star shells. Out of the 18 tests, 8 plugs remained intact, 2 split in two and the other 8 fragmented from 12 to about 70 pieces. These all landed within 5 m of the origin. Only one plug survived

the report shell tests. The others fragmented producing from 3 to 30 pieces, all landing within 25 m of the origin.

There does not seem to be any distinction between the tests performed with star shells at low and high temperatures. In both cases, none of the mortars burst. In the tests with the 76 and 102 mm sizes, the plug was simply blown out whole or split in two. With the 127 and 155 mm sizes, although the tube survived, the plug was fragmented to as many as 70 pieces. As a result, the mortar was usually left hanging in the test frame and only plug pieces were thrown to a maximum distance of 15 m.

Every mortar was burst by the report shells. The effect of the blast was very localized and there was no sign of crack propagation. Due to the many small pieces produced, the mass recovery, although fairly consistent, was never very high. It ranged from 78% to 85%. The number of mortar fragments recovered varied from 20 to approximately 130 and were found to distances of 35 m.

Aluminum Conduit Mortars

Although the aluminum conduit mortars were well made, the inside diameter was often found to be too small. Even with the wrapper removed, some shells had to be forced into the mortar. This problem became such a safety concern that testing of these mortars had to be suspended.

In general, when the burst was caused by report shells, the fractures were often of a brittle nature. Away from the centre of the burst location, the damage showed some signs of elongation. A similar effect was noted in the tests with star shells.

Out of the 18 tests, in only one did the plug remain fastened to the mortar. In the others, the plug was either blown

out intact (8 tests), split into 2 to 7 pieces (6 tests), or fragmented up to 33 pieces. Plugs or plug pieces were found to a maximum distance of 20 m.

In the tests with the star shells, the trend was towards more damage as the size increased. Except for the plugs being blown out, the 76 mm mortar tubes all survived. Also, one out of the three 102 mm, two out of the three 127 mm and all the 155 mm burst. The number of mortar pieces ranged from 2 to 17, with most being found within 80 m except for two which were thrown approximately 125 m from the source.

The report shells caused all the mortars to burst, producing much smaller and more numerous fragments than those in the star shell tests. The damage sustained by the 76 and 127 mm sizes was very similar, with the number of fragments ranging from 12 to 29 and being thrown to maximum distances of 80 m.

Sheet Steel Mortars

The sheet steel mortars behaved in a similar fashion to the aluminum except that they burst into larger and fewer pieces. The spot-welded plugs were either left intact in the mortar or blown out and bent. In a test with a report shell, a plug was blown out and also punctured.

Tested with star shells, all the 76 mm mortars survived. The 102 mm sizes also survived the high temperature tests but in two of the three low temperature tests, the plug was blown out of the tube. At both temperatures, the 127 and 155 mm mortars burst. The number of pieces recovered ranged from three to ten pieces with most being found within a 75 m radius. However, two pieces were found beyond this range; one at 90 m and the other at 113 m.

The report shells caused both the 76 and 127 mm mortars to burst. The tests performed at lower temperatures produced the most fragments as did the larger size shell. The number of fragments produced with the 76 mm mortars ranged from 3 to 13 and were found to a distance of 55 m. Tests on the 127 mm mortars produced from 12 to 20 fragments that were thrown to a maximum distance of 85 m. These maximum distances for the fragments were quite reproducible for both shell sizes.

Schedule-40 Steel Mortars

The results from the Schedule-40 steel mortars indicated that the star shells were not sufficiently energetic to cause any of them to burst. Also testing a 155 mm mortar three times at very low temperatures did not result in any damage. Only at sufficiently low temperatures, did the 127 mm report shells cause the mortar wall to crack and only under repeated firings at -35°C, did one eventually burst producing one fragment that was thrown a distance of approximately 65 m.

DISCUSSION OF RESULTS

In this section, some advantages and disadvantages of the various mortar materials and assembly methods will be discussed. The discussion will often be from the view that a well fastened plug is desirable. This is not necessarily so but is probably the norm when one assembles a mortar. The authors are not aware of anyone who is manufacturing a fireworks mortar with a built-in weakness as a safety design feature.

Mortar Plugs

In general, the use of a plug introduces at least two dissimilar materials in the manufacture of a mortar. One begins with a mortar tube, say paper, adds a wooden plug and fastens it with metal nails, screws or staples. Additionally, an adhesive could also be used. Due to the dissimilar thermal and mechanical properties of these materials, one must take care in the assembly process. Ideally, the components must work together to maintain a minimum required strength. Thus, the wood, and paper tube in this case, should not swell or shrink with humidity and temperature (including freezing and thawing) so as to work against the fasteners and each other. Above these often uncontrollable factors, are the forces experienced by a mortar during use.

It is difficult to maintain a rigid construction with a mix of component materials. Possibly, from the above point of view, the worst mix is a wooden plug with a metal or plastic tube. Metal is a good conductor relative to wood and it can quickly follow temperature fluctuations resulting in expansion or contraction that could result in the eventual loosening of fasteners.

As experienced by many, plastic mortars can attain very high temperatures when left in the direct rays of the sun. This could also lead to working against the plug fasteners.

Plugs are manufactured to be installed either with the grain perpendicular or parallel to the mortar tube. When installed with the grain oriented perpendicular to the tube, the plugs are normally cut as discs from softwood planks. To achieve the required thickness, it may be necessary to stack layers of the discs. When stacking, the grains of adjacent discs are oriented perpendicular to each other.

When the plug is to have the grain oriented parallel to the tube, it is either made from a single piece or laminated pieces of wood. The laminated plug is most often manufactured from hardwood. The plugs made from single pieces are turned from softwood stock or can be remnant cores from veneer manufacturing plants.

With either type of plug, it is important to have an appropriate thickness so that the assembly will increase the overall strength rather than weaken it. Plugs designed with the grain oriented perpendicular to the tube have some inherent disadvantages. The discs cut from planks will normally have one or two segments with short grain lengths that often result in breakage either during the curing or assembly process. It is possible to negate this shortcoming during assembly, by stacking discs so that the grain of each piece is oriented at right angle to the adjacent pieces. As already mentioned, the discs are usually nailed together with no adhesive. Thus, the effective thickness for fastening the plug to the tube remains the thickness of the individual planks. When assembling the mortar, the fasteners should be driven radially into the plug at the centre of every disc and perpendicular to the grain. This will prevent damaging the discs, will provide the strongest bond and will naturally stagger the fasteners around the mortar tube. To avoid splitting, care must be taken that not too many fasteners are driven onto the same plane.

The video and high speed film records indicated that the plugs may often be splitting as a result of striking the ground at high speeds. An example of this occurrence can be seen in Test 190.

Fasteners

The resistance of withdrawal (6,7,8) of fasteners from wood, not only depends on the type of fastener and wood but also on the orientation of the fasteners relative to the grain of the wood. All of these parameters can be controlled by the manufacturer. Economics, of course, does enter the picture.

Fasteners used in the assembly of mortars are subjected to lateral and withdrawal loads when in use. That is, if a force is applied along the axis of the mortar, (as by a piston) to bear only on the plug, the fasteners would experience a lateral load. Then, if the tube and plug material were of higher strength (and not easily deformed) than the fasteners, the fasteners would shear and the plug would be pushed out. However, since the plug is made of wood and since most mortar tubes are made of soft materials, they will normally experience some deformation. This deformation may result in the fasteners bending and giving rise to withdrawal loads.

The fast, high pressure transients produced by the lift charge causes the tube to experience a deformation that "simultaneously" loads the fasteners laterally and in withdrawal. These repeated loads will, eventually, cause loosening of the fasteners.

The resistance to withdrawal of wire nails is proportional to the length of embedment, the diameter of the nail and the specific gravity of the wood (assuming that no splitting occurs). The resistance to withdrawal per unit length is given by,

$P_{NW} = C_{NW} G^{2.5} D_N L_N$, where, P_{NW} is the resistance to withdrawal
C_{NW} is a constant
G is the specific gravity
D_N is the nail diameter
L_N is the nail length

The lateral resistance for common wire nails driven at least half their length in hardwood or two-thirds their length in soft wood is given by,

$P_{NL} = K_N D_N^{1.5}$, where, P_{NL} is the lateral resistance
K_N is a constant based on the type of wood
D_N is the nail diameter

The above equations are for wire nails driven into the side grain. As a general rule, when a nail is driven into the end grain, the holding power (withdrawal and lateral) is reduced by one-third. The load resistances obtained from the above equations are applicable only if there is no visible splitting. Recommendations for end and edge distances are 15 and 10 times the diameter of the nail (D_N), respectively and the very minimum being 5 D_N for both configurations. The recommended spacing of the nails is 20 D_N and 10 D_N when parallel and perpendicular to the grain, respectively. As an example, a plug with the grain oriented parallel to the tube should have nails driven at a distance equal to 15 times the diameter of the nail from the inside face of the plug. The next series of nails should be spaced at 20 D_N. Thus, if 3.25 mm diameter, 6.35 cm long nails are used, then for two rows of nails, the plug would have to be,

((15 X 3.25 mm) + (20 X 3.25 mm) + (15 X 3.25 mm)*), 16.25 cm long.

Note that the length in the last term, indicated by an asterisk does not have to be so large since the plug is loaded in only one direction; from within the mortar tube.

Although the recommendation for edge distances is less, the scenario for plugs manufactured with the grain perpendicular to the tube is complicated by the stacking and nailing of the discs. Normally no adhesive is used in this assembly. The safest approach with these is to drive the nails across the grain and at the centre of each disc so as to avoid splitting.

In hardwoods or where there is a possibility of splitting, all the distances mentioned above should be increased or nails should be driven into predrilled holes. The diameter of the holes should not exceed 80% of the diameter of the nail. Note that the wood should be well seasoned before it is installed. As lumber

dries, the fibres surrounding the nails relax and up to 75% of withdrawal resistance is lost. The same effect has been found with nailed joints that are subjected to continual wetting and drying.

Staples are thought to behave very much like nails. The same equations used for nails can be used to predict staple strengths. To provide comparable strength, the diameter of each leg, of a two-legged staple, must be about two-thirds the diameter of the nail.

Screws used for fastening plugs will be much more effective in reducing the possibility of them becoming loose since their withdrawal resistance per unit length, when driven into the side grain, is at least twice that of wire nails. It is given by,

$P_{SW} = C_{SW} G^2 D_S L_S$, where, P_{SW} is the resistance to withdrawal
C_{SW} is a constant
G is the specific gravity
D_S is the screw diameter
L_S is the screw length

It is not recommended that screws be loaded in withdrawal from end grain, but if necessary, their load bearing capacity must be reduced by one-third of that for side grain.

The lateral resistance for screws embedded at least seven screw shank diameters in the side grain of seasoned wood is given by,

$P_{SL} = K_S D_S^2$, where, P_{SL} is the lateral resistance
K_S is a constant based on the type of wood
D_S is the screw diameter

Predrilled holes should be 70% and 90% of the root diameter of the screw for soft and hard wood, respectively. Also note that the rules for installing lag bolts are similar to those for screws as outlined above.

Paper Mortars

Paper tubes have become attractive as mortar material due to their competitive costs. However, more than any other, paper mortars require frequent judgements as to whether to continue their use. These inspections are necessary since paper can be damaged by water, by unravelling, by heat and flame. The mass between the various types of paper mortars varied considerably not only because of the plugs used and the difference in length, but also due to their different densities. Their specific gravity was determined to be 0.75 for the plain convolute, 0.85 for the impregnated spiral and 0.80 for the "impregnated" convolute.

On the basis of the maximum distance to which fragments were thrown, the plain, convolute wound mortars were the worst performers. Fragments were recovered to distances of 75 m, whereas, fragments for the other two types of paper mortars were thrown only to maximum distances of 45 m. This is mainly due to the plain, convolute wound mortars having metric dimensions which results in a tighter fit and not so much on its construction. This increased confinement resulted not only in fragments being thrown farther but also in the production of many more and smaller fragments.

The video and high speed film records indicate that normally, the star shells simply blew the plugs out, causing flames to jet out of both ends and not damaging the tube. The larger star shells and report shells caused the mortars to burst with the star shells generally producing the larger mortar fragments. A spherical fireball accompanied this type of rupture.

Plastic Mortars

Many tests have been performed in Britain and the United States comparing PVC, ABS and HDPE. PVC has been abandoned as a mortar material and ABS is following the same fate. HDPE is now the most common plastic for the manufacture of mortars.

Some differences were found in the results between the series of tests on ABS1 and ABS2. None of the ABS1 mortars survived intact. In seven of the tests with star shells the tubes survived but the plug was blown out. The report shells burst all the mortars. Only seven of the plugs survived intact.

In the tests with star shells on the ABS2 mortars all but one burst in the 76 and 102 mm sizes. The 155 mm (available only as ABS2) mortars tested with star shells and all mortars tested with report shells also burst.

In general, many more and smaller fragments were produced with the ABS1 than the ABS2 mortars. The distribution of, and the maximum distance to which fragments were thrown was approximately the same for both types of ABS mortars.

HDPE is easy to work with. It normally has a substantial wall thickness that allows for rigid fastening of a plug. Care must be taken with this material since it has a tendency to shrink in the area where it is cut. The shrinking also seems to increase with use in the mouth region. Therefore, one must monitor the mouth of the mortar and make sure that it does not shrink to a dangerous level.

Tests were performed on 102 mm moulded and plugged HDPE mortars using a heat gun. Temperatures were monitored on the surface of the HDPE and half-way through its thickness. Heat was applied until the surface temperature reached approximately 130°C. The temperature in the HDPE was normally 25°C lower. The mortar was then allowed to cool and the diameter of the mortar was measured. This cycle was repeated four or five times for eight mortar samples. The changes in diameter were very similar for both mortars. The maximum increase in the inside diameter was 2.8 mm. It was possible to cause a larger change in the dimensions but this was normally accompanied by distortion and collapse of the mortar wall. This is very unlikely to occur during normal use.

In general, the results for the HDPE mortars indicate that the smaller star shells blew the plug out but large star shells and all report shells burst the mortar. The typical foldback of HDPE pipe as reported by others was displayed in several of the test results. Also, in HDPE, the transition point from brittle to ductile fracture seems to occur close to -35°C as indicated by the results of Test 240. The results indicate that the failure mode of HDPE mortars is much more acceptable than that of ABS.

A comparison made of the 76 and 102 mm mortar sizes that were common to both the plugged and the moulded HDPE mortars indicates the following results. Out of nine tests with star shells on the plugged mortars, only one burst and the plugs were blown out of the rest. All plugs and plug fragments were recovered within a 5 m radius. In the ten tests on the moulded mortars, 50% survived whereas the remainder suffered a small split with no associated fragments.

When making comparisons between these two types of mortars it must be remembered that the mass of the plugged mortar is approximately twice that of the moulded. In the tests with the report shells, comparisons can only be made with the 76 mm size. With the plugged mortar, the plug was either blown out intact or in pieces. The maximum number of fragments produced numbered 25 and were found to a maximum distance of 45 m. The report shell caused the bottoms of the moulded mortars to burst producing a maximum of 25 fragments that were found within a radius of 45 m. Taking the mass in consideration in tests with both types of shells, the performance of the moulded mortars is deemed superior.

Fibre Reinforced Epoxy (FRE) Mortars

When adjusted for the length, the fibre reinforced epoxy mortars were the lightest tested. Its specific gravity is 1.94. Although the tube material looks brittle, it can sustain

substantial deformation before cracking. It also has good shock absorbing properties. The FRE material is impervious to moisture over its surface, however, once cut, the fibres are exposed and moisture can penetrate through capillary action. This would not normally be a problem unless the moisture is allowed to freeze. Then fibre separation could lead to failure. FRE specifications(9) indicate that the water absorption according to ASTM D570-59 is 0.113% at room temperature over a 72 hour period. Corrective action, however, can be taken at the cut ends and holes with an appropriate sealing compound such as epoxy.

A concern that arises in the manufacture of mortars with this material is with regard to its thin wall and the possibility of damaging it. It would be more effective and less damaging to use a washer with either ringed nails or screws to fasten the plug. To further reduce damage and increase the integrity of the assembly, the plug should be round and well seasoned before installation.

Based on the distance that the fragments were thrown, and the fact that none of the tubes tested with star shells burst, this mortar was the best performer. The mortar normally shredded into small pieces that were composed of a few strands of fibre. The larger pieces were surrounded by loose fibres resulting in fragments with poor aerodynamics. As a result of this, the pieces were not thrown far.

Metal Mortars

The metal mortars tested were comprised of those manufactured from aluminum, sheet steel and Schedule-40 steel pipe. As indicated in Appendix B, the aluminum and sheet steel mortars were of approximately the same mass whereas that of the Schedule-40 steel mortars was seven times greater.

The advantage of aluminum for producing light-weight mortars was lost with the use of the wooden plug. Through the use of a welded aluminum plate, the mass could be greatly reduced but this would substantially increase the cost. As already mentioned, some of these mortars were not sized correctly. Proper sizes are available in the Schedule-40 pipe series but again these are more expensive and would more than double the mass of aluminum. The aluminum conduit used had a fairly thin wall. This requires some precautions when the plug is installed and would benefit from the use of washers to increase the load bearing area.

The high thermal conductivity value of aluminum (relative to wood), means that it can quickly follow temperature variations. That is, if a mortar is placed in the sun, its temperature will quickly rise whereas that of the plug will lag. The temperature rise will cause the aluminum to expand faster and more than the wood (assuming dry wood). As explained earlier, this will result in withdrawal loads against the fasteners that may eventually cause the plug to loosen.

Tests have indicated that both star and report shells burst these mortars with the report shell producing the smaller and more numerous sharp-edged fragments. As already stated, the majority of the fragments were found within 85 m except for one that was thrown to a distance of 125 m.

Sheet steel mortars were among the lightest tested. No problems are encountered with dissimilar materials in this design due to the "integral" plug. Again, due to the manufacturing process, the product was of consistent quality. Most of the 76 and 102 mm mortars survived the tests with star shells but the larger sizes and those tested with report shells suffered considerable damage. The majority of the fragments were found within 75 m except for a few that between 75 and 115 m.

Steel pipe mortars have been in use for many years. Due to steel's strength and availability it was easily accepted as mortar material. Based only on the number of mortars that burst, Schedule-40 steel mortars would be deemed the best. It must be kept in mind that in the Preliminary Tests, the butt-welded bottoms were often blown off. This led to a re-design. The plug plate diameter was machined to the inside diameter of the pipe, inserted a depth equal to the plate into the pipe and continuously welded on the perimeter.

Mortars suffered damage only with report shells and then, some only at low temperatures and/or after multiple testing. Why were so few mortars damaged in the tests? In use, bursts are reported regularly. It has been suggested that the shells used in the tests were not the most powerful. It must be stated, however, that the Schedule-40 steel mortars made at CERL were manufactured from new steel pipe and welded by a licensed welder. The same cannot be said about other steel mortars in use. One cannot assume that all pipes and tubes are commercially manufactured and as such, are welded or fused to some standard by a licensed welder.

Observations made on many steel mortars in use by various operators revealed that the inside surface of the pipes was often very rough. Some seemed to have the graininess of cast iron. This could be caused by the corrosive action of the combustion products of the lift charge. However, it has also been admitted that used pipe is often purchased to manufacture mortars. This practice should be avoided since it is difficult to determine the type of steel or the working environment (chemical or temperature cycling) that it has been subjected to. The type should be known to avoid easily hardenable steels and to ensure proper welding. Since resistance to impact depends on the ductility (10), steels with a high modulus of toughness should be selected.

Other effects that may lead to a steel pipe failing (i.e. a mortar bursting) include fatigue and surface modification. Fatigue

refers to a repeated-load phenomena such as would occur on the crankshaft of an engine. Although the frequency of loading is much lower in mortars than that which would be encountered in the crankshaft example, the loading is accompanied by other phenomena as described below. Generally, the number of repeated loadings to cause failure depends on the magnitude of the load. Failure by fatigue is due to progressive cracking which eventually leads to catastrophic (i.e. brittle) fracture. Fatigue cracks start at a point of maximum stress at a point of stress concentration referred to as a stress raiser. Stress raiser are found within the metal as voids or inclusions of foreign matter and on the surface of the metal as rust pits, scratches, etc. In failures caused by fatigue, the initiation point can usually be determined. Also, progression of the crack will cause the appearance of rings radiating from the point of origin.

The other effect that is being considered that may cause hardening and premature failure is that of surface modification of steel, by chemical adjustments, through repeated use. In the presence of gaseous carbon compounds and heat and pressure, carburization can occur. Carburizing is the process by which carbon is introduced into a solid, iron-base alloy (steel) by heating above the transition temperature while in contact with a carbonaceous material. On ignition of the lift charge, carbon compounds, high temperatures and pressures are all present, although for a short period of time. Carbon increases the hardness of steel and in the case of a steel mortar, the result may be a pipe having a hard (brittle) internal surface and a tough exterior. This topic remains to be investigated.

SUMMARY

The results do not indicate serious faults with any particular mortar material. The low temperature tests indicate that there is an effect and an investigation of the ductile to brittle

transition or glass transition temperature is in progress for the various mortar materials.

Except for the Schedule-40 steel which burst only at very low temperatures, all other mortars ruptured and produced fragments under most conditions. Safety criteria can then be based on the number and mass of the fragments produced and the distance to which the fragments were thrown. The fragments from the fibre reinforced epoxy mortars had a range of approximately 30 m, the paper 70 m, the plastics 70 m and the metal mortars 120 m. The lethality of these fragments and the blast overpressures were not considered here but will be the topic of a future report. Also, the debris distribution data is being condensed for the various mortar materials to provide a better overview of the danger posed by the fragments to operators and spectators.

The data generated from this study can and will be used as a guide to develop mortar standards and improve the construction of existing mortars and possibly lead to new designs.

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APPENDIX A - List of Contributors

CANADA

Brault, P., Fiatlux, Inc

Brown, R., Hands Fireworks Inc

Cardinal, M., Ampleman Pyrotechnics

Masson, B., BEM Fireworks

UNITED KINGDOM

Wharton, R., Health and Safety Executive,

UNITED STATES

Blot, F., Vineland Fireworks Co. Inc
(Fireworks by Girone)

Conkling, J., American Pyrotechnic Association

Grucci, F., Fireworks by Grucci Inc

Hill, C., Pyrotechnic Guild International Inc

Souza, R., Pyro-Spectaculars Inc

Spielbauer, P., Spielbauer Fireworks Co. Inc

Tucker, E., Pyrodyne Aerial Productions
(PyroSpectaculars North West)

Weeth, C., Mighty-Mite Marketing, Inc

APPENDIX B - Mortar Specifications

Mortar Material	Size /mm	Mass /g	Inside Diameter /mm	Wall Thickness /mm	Inside Length /cm	Plug Length /cm
Paper-P-S	76	430	72	5.2	36.3	3.5
	102	1770	99	10.2	55.2	4.8
	127	3400	123	12.4	71.9	5.7
Paper-I-S	76	1190	76	10.2	52.1	4.4
	102	2680	101	12.9	65.4	5.7
Paper-I-C	102	2160	103	10.7	52.1	10.8
	127	3960	128	12.7	72.7	13.0
HDPE+Plug (Sample 1)	76	1260	77	6.4	73.3	3.5
	102	1720	102	6.4	68.6	7.9
	127	2720	125	7.8	68.9	8.0
	155	4730	159	8.7	79.5	11.9
HDPE+Plug* (Sample 2)	127	3020	126	6.9	74.2	9.5
	155	4210	152	7.3	81.0	9.8
HDPE-Mould#	76	590	80	4.3	46.5	0.7
	102	1280	104	6.2	61.0	0.9
ABS	76	950	77	5.3	46.5	5.2
	102	1890	102	5.2	66.0	6.5
ABS-RDwood	76	1320	77	5.7	40.6	11.4
	102	2450	102	6.5	53.3	15.2
	155	6210	153	7.6	61.0	22.9
Fibre	76	470	76	1.6	48.3	5.0
	102	810	103	1.6	54.0	6.9
	127	1430	127	2.4	53.0	7.9
	155	2530	152	2.5	83.0	8.1
Aluminum	76	530	73	1.3	40.2	6.0
	102	1500	97	2.2	70.8	5.4
	127	2110	123	2.1	68.9	7.3
	155	2690	148	2.3	68.3	7.8
Sheet Steel	76	970	76	0.8	46.6	0.8
	102	1560	102	0.8	53.3	1.5
	127	1960	127	0.8	52.1	1.5
	155	2520	151	0.8	57.8	1.5
Steel Sched-40	76	6700	76	5.5	50.8	1.3
	102	10400	102	6.0	55.9	1.3
	127	14700	128	6.6	54.9	1.3
	155	20800	154	7.1	60.3	1.3

#See manufacturer's specification sheet for detail dimensions.

APPENDIX C - Shell Specifications

Shell Type	Shell Shape	Size /mm	Lift Charge Mass/g	Composition Mass/g
Star	Cylindrical	76	28	142
	Spherical	102	57	138
	Spherical	127	85	236
	Spherical	155	113	771
Report	Cylindrical	76	28	43
	Cylindrical	127	71	99

APPENDIX D - Mortar Material Properties

Thermal coefficient of linear expansion

Wood (Note that for wood, thermal expansion is often overshadowed by the larger dimensional changes due to moisture content.)

Longitudinal grain - 3.4 X 10^{-6}/°C (Independent of specific gravity)
Across grain radial - 25.7 X 10^{-6}/°C (Specific gravity of 0.46)
Across grain tangential - 34.8 X 10^{-6}/°C (Specific gravity of 0.46)

Paper	- N/A
HDPE	- 15 to 30 X 10^{-5}/°C
ABS	- 8.5 X 10^{-5}/°C
PVC	- 5.0 to 14.8 X 10^{-5}/°C
Fibre (Resin)	- 2.2 X 10^{-5}/°C
Steel	- 1.4 X 10^{-5}/°C
Aluminum	- 2.4 X 10^{-5}/°C

Thermal conductivity in W/m °C

Wood - 0.059 to 0.171 (Heat flow across grain in Balsa to Red Oak. Heat flow parallel to the grain is 2 to 3 times higher.)

Insulating fibreboards	- 0.045
HDPE	- 0.33
ABS	- 0.14 to 0.21
PVC	- 0.12 to 0.17
Fibre	- 0.29
Steel	- 35 to 70
Aluminum	- 225

Specific gravity

Wood	- 0.16 to 0.67 (Balsa to Red Oak)
Paper	- 0.80
HDPE	- 0.95
ABS	- 1.06
PVC	- 1.35
Fibre	- 1.94
Steel	- 7.80
Aluminum	- 2.71

APPENDIX E - Mortars Tested

Mortar Type	Shell Type	Nominal Temp/°C	Mortar Size	Test Numbers
Paper-Plain-Conv (26 Trials)	Star	-20	76	231,232,233
			102	012,151
			127	002,009
		20	76	213,214
			102	197
			127	145,152,171
	Report	-20	76	015,016,167
			127	001,010,144,168
		20	76	161,164,165
			127	143,163,166
Paper-Impreg-Spiral (13 Trials)	Star	-20	102	003,011,198
		20	76	207,208
			102	170,215
	Report	-20	76	013,014,169
		20	76	142,153,160
Paper-Impreg-Conv (10 Trials)	Star	-20	102	149,150
			127	004,005,007
		20	102	146,147,148
	Report	-20	127	006,008

Mortar Type	Shell Type	Nominal Temp/°C	Mortar Size	Test Numbers
HDPE + PLUG				
Sample 1 (30 Trials)	Star	-20	76	223,224,236
			102	020,087
			127	086,088
			155	024,085
		20	76	201,202
			102	080,196
			127	079,172,188
			155	078,173,187
	Report	-20	76	019,083
			127	084,089,240
		20	76	081,174,182
			127	082,175,176
Sample 2 (13 Trials)	Star	-20	127	072
			155	023,073
		20	127	067,190
			155	066,186,189
	Report	-20	127	075,184
		20	127	069,178,180
HDPE - Moulded (16 Trials)	Star	-20	76	225,226,235
			102	018,050
		20	76	199,200
			102	127,128
		SUN	102	129
	Report	-20	76	017,090,177
		20	76	049,051
		SUN	76	132

Mortar Type	Shell Type	Nominal Temp/°C	Mortar Size	Test Numbers
ABS (14 Trials)	Star	-20	76	221,222
			102	071
		20	76	205,206
			102	068,194,195
	Report	-20	76	141,183,185
		20	76	070,179,181
ABS - Hardwood Plug (11 Trials)	Star	-20	76	217,218
			102	139
			155	138
		SUN	102	134
		20	102	193
		SUN	155	133
	Report	-20	76	140
		SUN	76	135
		20	76	158,159
Fibre (30 Trials)	Star	-20	76	219,220
			102	056,096,097
			127	058,098,099
			155	025
		20	76	203,204
			102	057,100,101
			127	060,102,104
			155	059
	Report	-20	76	054,106,108
			127	055,110
		20	76	052,107,112
			127	053,105,109,111

Mortar Type	Shell Type	Nominal Temp/°C	Mortar Size	Test Numbers
Aluminum (18 Trials)	Star	-20	76	216
			102	021
			127	022
			155	026
		20	76	210
			102	046,192
			127	047,162
			155	048,191
	Report	-20	76	065
		20	76	063,064,137
			127	061,062,136
Sheet Steel (35 Trials)	Star	-20	76	229,230,234
			102	039,093,123
			127	040,092,122
			155	027,091,120
		20	76	211,212
			102	042,045,124
			127	043,121,125
			155	044,119,126
	Report	-20	76	041,094,095
			127	237,238,239
		20	76	076,131,156
			127	077,130,157
Steel Schedule-40 (29 Trials)	Star	-20	76	227,228
			102	035
			127	036
			155	037,245/247*
		20	76	209
			102	029,117
			127	031,116
			155	032,115
	Report	-20	76	033,118
			127	034,038,241,242/244*
		20	76	028,114,154
			127	030,113,155

Mortar Type	Shell Type	Nominal Temp/°C	Mortar Size	Test Numbers
Preliminary Tests (15 Trials)				
HDPE + Plug	Star	5	102	264-P
HDPE - Moulded			102	262-P
Fibre			102	260-P
Sheet Steel			102	255-P
Sheet Steel			127	257-P
Steel Schedule-40			127	249-P/250-P*
HDPE - Moulded	Report	5	76	261-P,263-P
Fibre			76	259-P
Sheet Steel			76	256-P
Sheet Steel			127	258-P
Steel Schedule-40			76	248-P,251-P,252-P

Impreg - Impregnated
Conv - Convolute
* - Tests performed on the same mortar